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SCANNING PHOTOVOLTAGE INVESTIGATION OF SILICON- AND GALLIUM ARS--ETC
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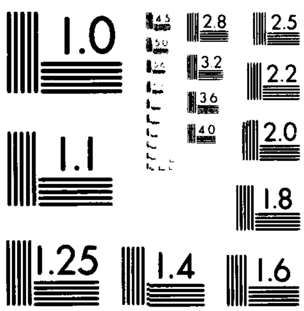

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(10) R. L. STREEVER
J. J. WINTER
ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The scanning photovoltage technique was used to image the semiconductor-oxide interface region of MOS capacitors based on silicon and on GaAs. The technique gives a "photovoltage image" of optically active defects at the interface. Various types of defects and gross imperfections were observed. In the case of the GaAs MOS capacitors, a high density of gross imperfections resulting from surface damage was observed on lightly etched samples. Heavier etching was noted to eliminate this damage and the lower defect density can be correlated with improved device performance.

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SCANNING PHOTOVOLTAGE INVESTIGATION OF SILICON- AND GaAs-BASED MOS CAPACITORS

R. L. STREEVER AND J. J. WINTER

U.S. Army Electronics Technology and Devices Laboratory (ERADCOM), Fort Monmouth, N.J. 07703 (U.S.A.)

1. INTRODUCTION

As integrated circuits become smaller and more complex there is an ever-increasing need for methods of probing semiconductor surfaces and device interfaces for defects and irregularities. In the photoscanning technique[1,2] a light beam is scanned across the surface of the semiconductor. Any change in the photoresponse (photovoltage, photocurrent etc.) can then be detected and monitored as a function of the position of the light spot on the surface. Since the photoresponse is sensitive to electrically active defects, the technique provides a way of mapping the defect concentration on the surface. The map is realized by displaying the photoresponse on the z input of an x-y-z oscilloscope and the light beam deflection on the x and y inputs. In this way an image of the semiconductor surface is displayed on the rastered oscilloscope face, with x input (controlling the trace brightness) being modulated by the photoresponse.

The operation of the photoscanner is quite similar to that of scanning electron microscopy (SEM) and in fact by collecting the SEM beam-induced current the two techniques can be made quite analogous[3]. The advantage of the SEM technique lies largely in its excellent resolution, but its complexity and the necessity for a high vacuum to some extent limit the method. The advantages of the photoscanner lie in its relative simplicity, its direct probing of optically active defects and its potential for automatic and non-destructive evaluation of devices.

DiStefano and coworkers[1] have recently shown that the scanning photovoltage (SPV) technique can be a particularly useful way of studying the interfaces of MOS capacitors. By using a highly focused laser beam as the light source they have significantly increased the resolution of the technique and they have presented some results for silicon-based MOS capacitors. We have recently characterized both silicon- and GaAs-based MOS capacitors and the purpose of this paper is to report on SPV studies of these devices.

A brief phenomenological description of the photovoltage effect as it applies to MOS capacitors is given in Section 2. This is followed in Section 3 by a brief discussion of the experimental technique. In Section 4 results obtained using both silicon- and GaAs-based MOS capacitors are presented.

1. For a number of references to the photoscanning technique see the following:
   T.H. DiStefano, ARPA Rep. RADC-TR-76-160, 1976, p 27;
   J.W. Phibrick and T.H. DiStefano, in 13th Int. Symp. on Reliability Physics, Las Vegas, 1975, IEEE, New York, 1975.
2. Lile and Davis, Solid-state Electron., 18(1975)669.
3. W.R. Bottoms, D. Guterman and P. Roitman, J. Vac. Sci. Technol., 12(1975) 134.

2. PHOTOEFFECTS IN MOS CAPACITORS

The usual MOS capacitor having a thin insulating layer of SiO_2 deposited on a silicon substrate is shown in Fig. 1. For optical studies the aluminum front contact is made thin (about 150 Å) so that it is optically transparent and light can penetrate to the silicon.

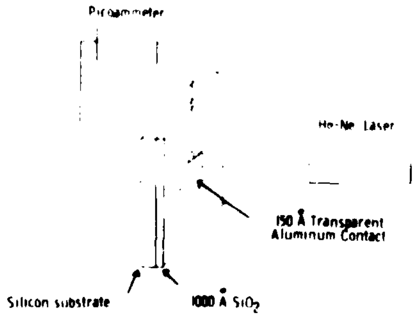


Fig. 1 A simplified diagram of the system used for photovoltage studies of MOS capacitors. In the experiments the laser beam could be scanned across the surface.

The theory for the generation of a surface photovoltage in such a device is, qualitatively at least, quite simple. The energy of the incident light must be greater than the semiconductor band gap so that electron-hole pairs can be created but must be less than the energy needed to cause photoemission from the semiconductor to the conduction band of the insulator. For silicon or GaAs with band gaps of about 1.1 eV and 1.4 eV respectively the former requirement is met by the 2 eV light from a He–Ne laser (wavelength 632 nm). Assuming that the insulating layer is SiO_2, this energy is less than that needed to cause photoemission into the insulator. If the capacitor is then biased in the direction of inversion the optically generated minority carriers move to the surface where they give rise to a photovoltage. If the light is then chopped or scanned, so that an a.c. component of the photovoltage is developed, this component can be measured by means of a suitable detecting circuit connected across the MOS capacitor.

Clearly the photovoltage will be sensitive to changes in minority carrier generation or recombination and thus can detect optically active defects.

3. EXPERIMENTAL TECHNIQUES

3.1. *Scanning photovoltage system*

The SPV system used was similar to that described by DiStefano and Viggiano[4]. The system uses a He–Ne 632.8 nm (visible red) laser which is focused on the sample to a spot size of about 1 μm. Mirrors in the optical path permit the beam to be scanned across the semiconductor surface. By synchronizing the mirror drives with the x and y axes of an x–y–z oscilloscope the image of the semiconductor surface can be displayed on the oscilloscope, as discussed in Section 1. Changes in the photovoltage as the light beam passes over defects are detected by means of a sensitive current amplifier connected across the MOS capacitor. The amplifier

4. T.H. DiStefano and J.M. Viggiano, IBM J. Res. Dev., 18(1974)94.

output is directed in turn to the z axis of the oscilloscope so that changes in photovoltage are shown by changes in the brightness of the oscilloscope trace. In this way a "photovoltage image" of the sample surface is displayed on the oscilloscope. Since the a.c. circuitry is sensitive only to changes in photovoltage, the z input to the oscilloscope monitors essentially the derivative of the photovoltage as the light beam is scanned across the surface.

In experiments in which it was required to probe one point on the sample surface and to measure the photovoltage as a function of some parameter such as a sample bias, it was found to be convenient to introduce a chopper into the optical path. This permitted the generation of an a.c. photovoltage independent of the scanning. The in-phase and out-of-phase components of the photovoltage (with respect to the light signal) could then be detected separately by phase-sensitive detection.

3.2. Samples

3.2.1. Silicon samples

Preliminary studies were made using MOS capacitors fabricated on ⟨100⟩ orientation p-type silicon wafers with resistivities of 2–4 Ω cm. The wafers were thermally oxidized in dry oxygen at 1000 °C to form an SiO_2 layer about 870 Å thick. An array of transparent aluminum front contact dots approximately 150 Å thick was deposited by electron beam evaporation through a mechanical mask. Thicker contacts were deposited on the edge of the transparent ones to facilitate electrical connection and an aluminum back contact was also deposited.

A second set of MOS capacitors was fabricated on ⟨111⟩ orientation p-type silicon wafers with resistivities of 1.5–2.0 Ω cm. The dry thermal oxide was about 1000 Å thick. Transparent aluminum contacts (approximately 125 Å thick and 2 mm square) were defined by photoresist techniques and were deposited by electron beam evaporation. Thicker contacts (approximately 10000 Å) smaller in area were also deposited to facilitate electrical connection. One set of samples was left unannealed and another set (from the same wafer) was given a final nitrogen anneal at 500 °C.

Capacitance (C–V) and conductance (G–V) measurements were performed on the "photoresist samples" to characterize the surface state density. Further details of the investigation have been reported elsewhere[5]. The unannealed samples were found to have a rather large surface state density, possibly arising from the electron beam irradiation the samples underwent during contact deposition. The annealed samples showed a markedly reduced surface state density over most of the silicon band gap.

3.2.2. GaAs samples

The GaAs MOS capacitors were fabricated by depositing a layer of SiO_2 between 1000 and 1500 Å thick onto n-type GaAs using the chemical vapor deposition technique. The substrate material had a ⟨100⟩ orientation and a carrier concentration of 6×10^{16} cm^{-3}. For photovoltage studies an array of transparent gold front contacts was deposited. Indium dots were melted into the GaAs to provide an ohmic back contact.

Before oxide deposition the polished substrate material was subjected to two different etching treatments. One set of wafers was etched lightly using an HCl-based etch while the other set was etched for about 1 min using a solution of 2.5 parts 95% H_2SO_4:1 part 30% H_2O_2:1 part H_2O to remove about 3 μm of the surface. As will be reported elsewhere[6] the H_2SO_4-etched samples showed much better electrical properties. We show in Section 4 that this correlated with a lower density of surface imperfections in these samples.

5. R.L. Streever, J.J. Winter & F. Rothwarf, Proc. Electrochem. Soc., 77(2)(1977)393.

6. R.L. Streever, J.T. Breslin and E.R. Ahlstrom, Solid State Electron., in the press.

4. RESULTS AND DISCUSSION

4.1. *Silicon results*

4.1.1. *Preliminary studies*

Before studying the samples in the normal scanning mode some studies of the photovoltage as a function of sample bias or of band bending were carried out using the system with the light-chopper as previously discussed. The results of these photovoltage bias studies and their correlation with C–V and G–V measurements have been discussed more fully in our previous paper[5]. As shown in that paper, surface state peaks could be observed in the photovoltage–bias curves as well as in the C–V and G–V curves and good correlation between photovoltage, capacitance and conductance measurements was obtained. The overall photovoltage increased as expected as the sample was biased into inversion.

The p-type silicon MOS capacitors were found to be inverted even with no sample bias applied. This "permanent" inversion channel present in p-type samples arises from the positive charges in the oxide which attract the minority carriers to the interface. This inversion channel captures the locally generated cloud of minority carriers[1] and permits the photovoltage to be excited not only directly through the transparent contact but also at points well away from it, since minority carriers can travel via the inversion channel to the contact. Thus it was possible to obtain scanning photovoltage images of regions adjacent to the transparent contacts as well as of the region under the contact.

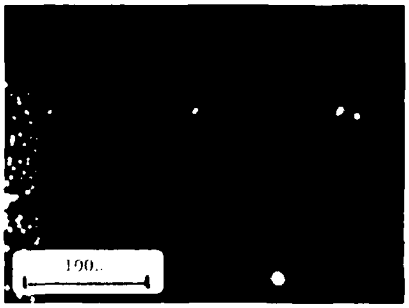
4.1.2. *Scanning photovoltage*

Most of the SPV images were obtained using the MOS capacitors fabricated from the ⟨111⟩ silicon wafers. Typical images are shown in Fig. 2. In Figs. 2(a) and 2(b) the region under the contact as well as regions adjacent to the contact can be seen while in Fig. 2(c) the scanning is entirely off the transparent contact. The bright spots under the contact region are caused by the more intense signals in that region which tend to overload the brightness control on the x–y–z oscilloscope. (To be more precise the background light intensity is controlled by the bias level of the z input to the oscilloscope. The signal from defects must be smaller than this in order to modulate the background. Otherwise poor images with loss of background result.)

Considering first just the region away from the contact we see that, in general, point-like defects are observed over most of the surface, and in some cases these tend to be along lines or ridges. Also in some regions of the surface the defects are much more highly concentrated.

5. Streever et al, Proc. Electrochem. Soc.,77

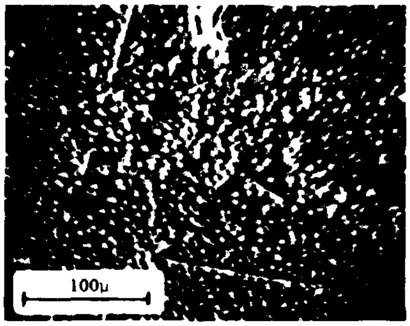
(a)



(b)

(c)

Fig. 2. SPV images of the surface of a ⟨111⟩ orientation annealed silicon MOS structure. The transparent contact is seen on the left in (a) and (b) while in (c) the scanning is entirely off the contact region.



(a)

(b)

Fig. 3. SPV images of the annealed ⟨111⟩ orientation silicon MOS structure showing (a) only the region under the transparent contact and (b) an enlarged image of a similar region.

Images of the region under the transparent contact obtained with the signal levels appropriately adjusted are shown in Fig. 3(a) and, enlarged, in Fig. 3(b). We see that the structure under the contact is quite different from that observed adjacent to

the contact. The difference in structure observed on scanning under the contact seems to be greater than can be explained by the stronger signals alone and it seems that an entirely different structure is being observed. The structure observed under the contacts probably originates from fine pinholes in the thin aluminum contacts. The contacts may also induce perturbations in the underlying oxide.

Studies were also made using the MOS capacitor fabricated from the $\langle 100 \rangle$ orientation silicon wafer for which the aluminum contacts were evaporated through a mechanical mask. A typical image obtained by scanning through the contact is shown in Fig. 4. It is curious that the image is more like that obtained by using the $\langle 111 \rangle$ capacitors and scanning away from the contact. This suggests that to some extent the additional structure under the contacts may be peculiar to the $\langle 111 \rangle$ samples and may arise from the somewhat different processing they undergo.

Fig. 4. SPV image obtained on scanning through the transparent contact of the $\langle 100 \rangle$ orientation silicon MOS capacitor prepared by evaporating aluminum contacts through a mechanical mask.

4.2. *GaAs results*

Both the lightly etched (HCl-etched) and the more heavily etched (H_2SO_4-etched) samples were investigated. Most of the photoscanning was carried out using zero bias which corresponds to depletion. As with the silicon samples some pictures were obtained by scanning directly through the transparent contact to which the electrical connection had been made. As a result of minority carrier diffusion and the formation of a localized cloud of minority carriers at the surface[1] it was also possible to obtain a photoresponse by scanning through or between adjacent contacts up to three contacts away. The images obtained with the HCl-etched samples showed ridges and lines over most of the surface probably resulting from the work damage the wafers received during sawing and polishing. Typical images are shown in Fig. 5; Fig. 5(a) was obtained by scanning through the active contact to which the electrical connection had been made while Figs. 5(b) and 5(c) were obtained by scanning through neighboring contacts. Results similar to Figs. 5(b) and 5(c) were obtained on scanning between contacts. The grainy structure (Fig. 5(a)) was observed only on scanning directly through the active contact indicating that some loss of resolution occurred when scanning away from the active contact to which the electrical connection had been made.

The images obtained with the H_2SO_4-etched samples showed almost no lines or ridges indicating that most of the work damage was removed by the etching. Many regions of the samples showed no defects at all. Some defects observed on scanning between contacts are shown in Fig. 6. Figure 7(a) shows an image produced

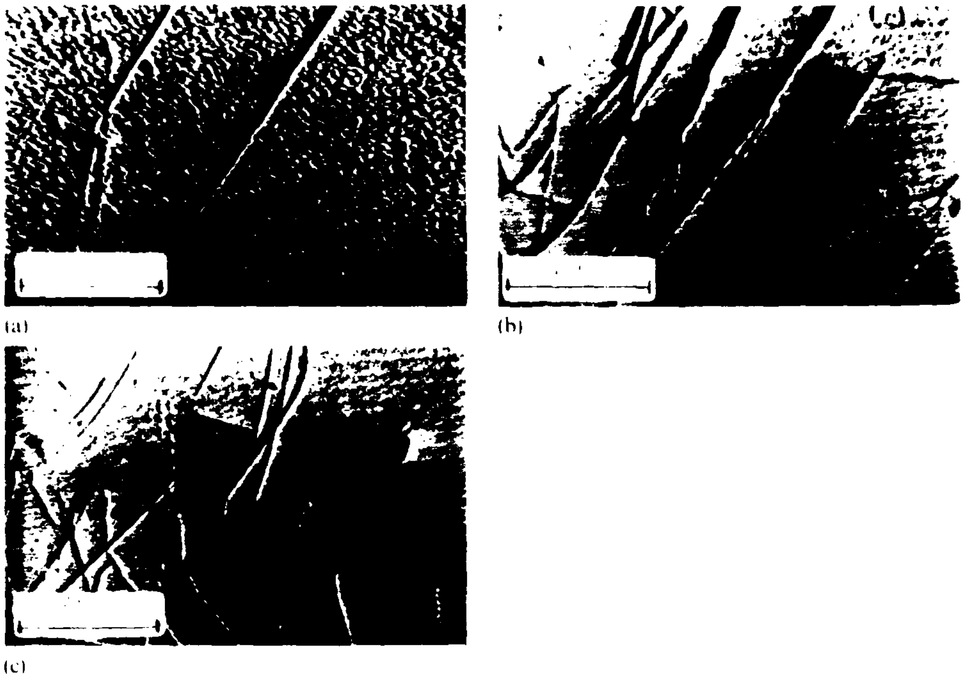


Fig. 5. SPV image obtained using the HCl-etched GaAs MOS capacitors. (a) was obtained by scanning directly through the active transparent contact while (b) and (c) were obtained by scanning through neighboring contacts.

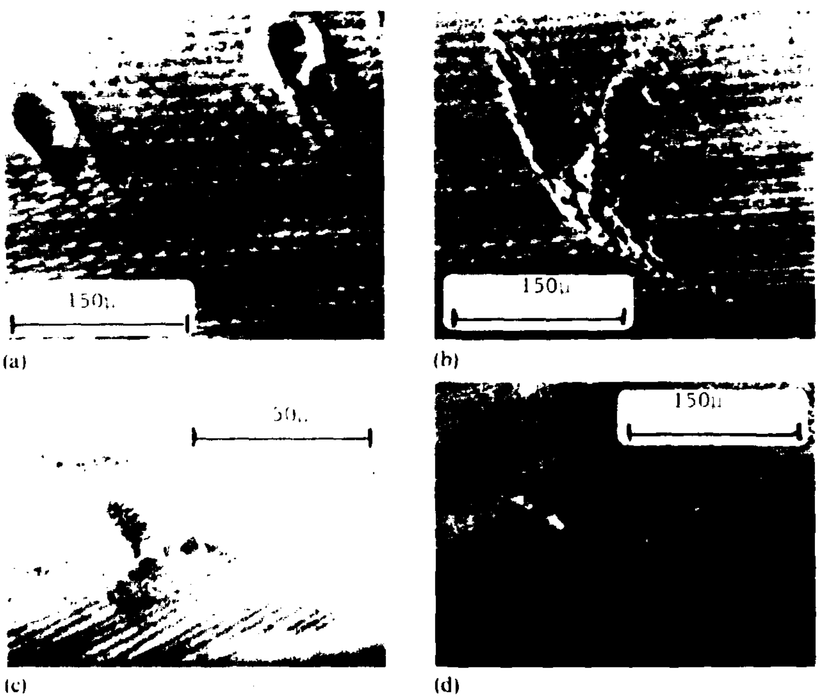
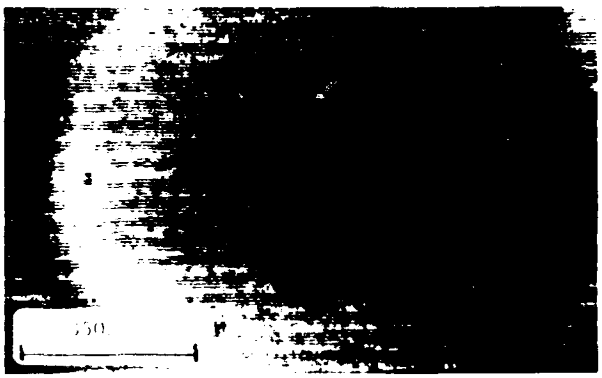


Fig. 6. SPV images obtained by scanning between contacts using the H_2SO_4-etched GaAs MOS capacitors.

by scanning through a contact neighboring the active contact while Fig. 7(b) shows a similar image of a complete contact. Finally Fig. 8 shows the edge of a contact and a number of defects.

(a)



(b)

Fig. 7. SPV images obtained by scanning through contacts neighboring the active one using the H_2SO_4-etched GaAs MOS capacitors. (a) shows a part of a contact while (b) shows the complete contact.

Fig. 8. SPV image obtained using the H_2SO_4-etched GaAs MOS capacitors, showing a number of defects near the edges of the contacts

5 CONCLUSIONS

The SPV technique seems to be an excellent method for studying both defects and gross irregularities on semiconductor surfaces and interfaces. Advantages of the method lie in its simplicity and in the relatively good resolution that can be obtained. The technique is relatively non-destructive. By using a tiny mercury probe and scanning in the region around it the need for a transparent metal contact could be eliminated. The technique could then be used to examine semiconductor devices before the contacting electrodes were deposited.

In this paper we have attempted to show some typical applications of the techniques using both silicon- and GaAs-based MOS capacitors and also to point out some complications that arise in the detailed analysis of the photovoltage images. In the case of GaAs, sawing and polishing seems to leave a rather large degree of surface damage and a clear correlation between the electrical measurements and the SPV images was found. A more detailed investigation of damage-free and selectively etched GaAs surfaces would be interesting in order to characterize defects more fully and to develop the full potential of the technique.

A more detailed correlation of localized defects with the measured electrical properties of a device would also be of interest. For example, a scan displaying the photovoltage *versus* position on the wafer showed that the doughnut-shaped defects near the edge of the contact of Fig. 8 exhibited an unusually high photovoltage. With a small contact, even a few such defects could conceivably have a large effect on the device performance.

ACKNOWLEDGMENTS

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